Lattice Activities

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Outline

I. Introduction: Lattice @BNL…very special for over ¼ century!

II. Hunting New Physics with the lattice

III. Summary & Outlook

Introduction

- Lattice studies/simulation very special part of BNL-activities for over quarter of a century! …..**Michael Creutz's** name is essentially synonymous with lattice simulation…pioneering work now blossomed into a significant component of High Energy & Nuclear Physics communities.
- **'05 heralds significant new developments @BNL**:

  a) QCDOC 10 Tf ….RBC machine

  b) arrival of **Frithjof Karsch**….adds important new directions in the arena of finite temperature simulations.

  c) QCDOC 10 Tf ….DOE machine

  d) RBC joins forces with UKQCD

II. Hunting New Physics with the lattice

- 1) Recapitulate: why lattice is needed
- **2) Lattice helps reach a milestone in Particle Physics**
- **3) Precise determination of the unitarity triangle… THE HOLY GRAIL**
- 4) Exact chiral symmetry on the lattice
- 5) **20 years of B_K**
- 6) RBC-Menu'05
- **7) B versus K-UT**

Why Lattice is Needed

Due to the non-perturbative nature of low energy QCD, many experimental results, often attained at enormous cost cannot be used effectively to test the Standard Model unless accurate values of hadronic matrix elements are known; lattice is the only reliable tool for such calculations

$|\varepsilon_K|$ (BNL '64; Christenson et al), provides a
CLASSIC EXAMPLE.

$$
\begin{aligned}
|\varepsilon_K| \quad &= \quad \hat{B}_K C_K \lambda^6 A^2 \bar{\eta} \{ \eta_1 S(x_c) + \eta_2 S(x_t) [A^2 \lambda^4 (1 - \bar{\rho})] \\
&\quad + \eta_3 S(x_c, x_t) \} \qquad C_K = \frac{G_F^2 f_K^2 m_K m_W^2}{6\sqrt{2}\pi^2 \Delta m_K}
\end{aligned}
$$

The experimentally known value $|\varepsilon_K| = 2.27 \times 10^{-3}$ can be used to extract information on the poorly known SM parameters $\bar{\rho}$ and $\bar{\eta}$, once the non-perurbative quantity, B_K becomes known, as everything else on the RHS is known quite well.

$$V_{\mathrm{CKM}} =$$

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix} .$$

(12.

CKM-matrix in the Wolfenstein Representation (PDG'04)

PDG'04

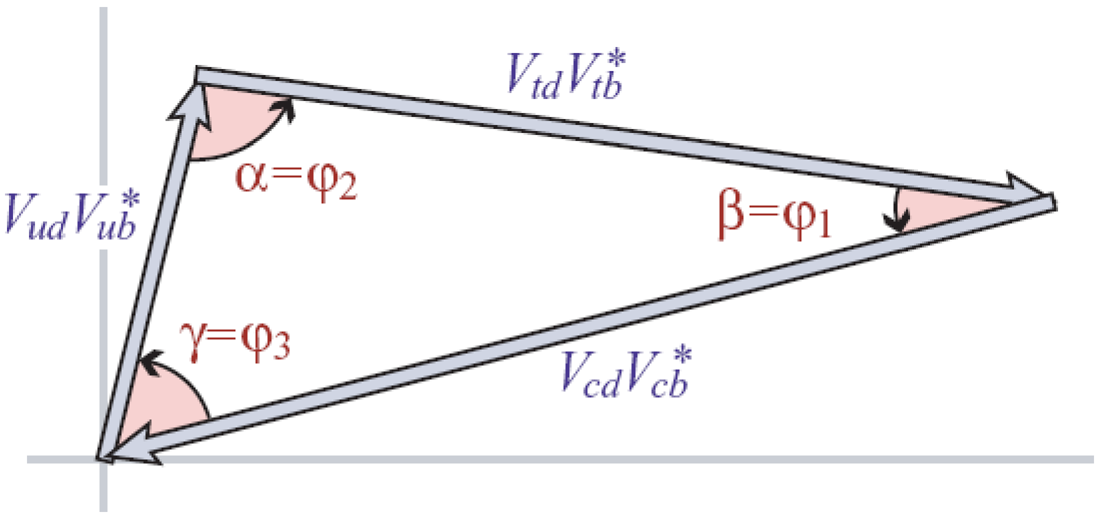
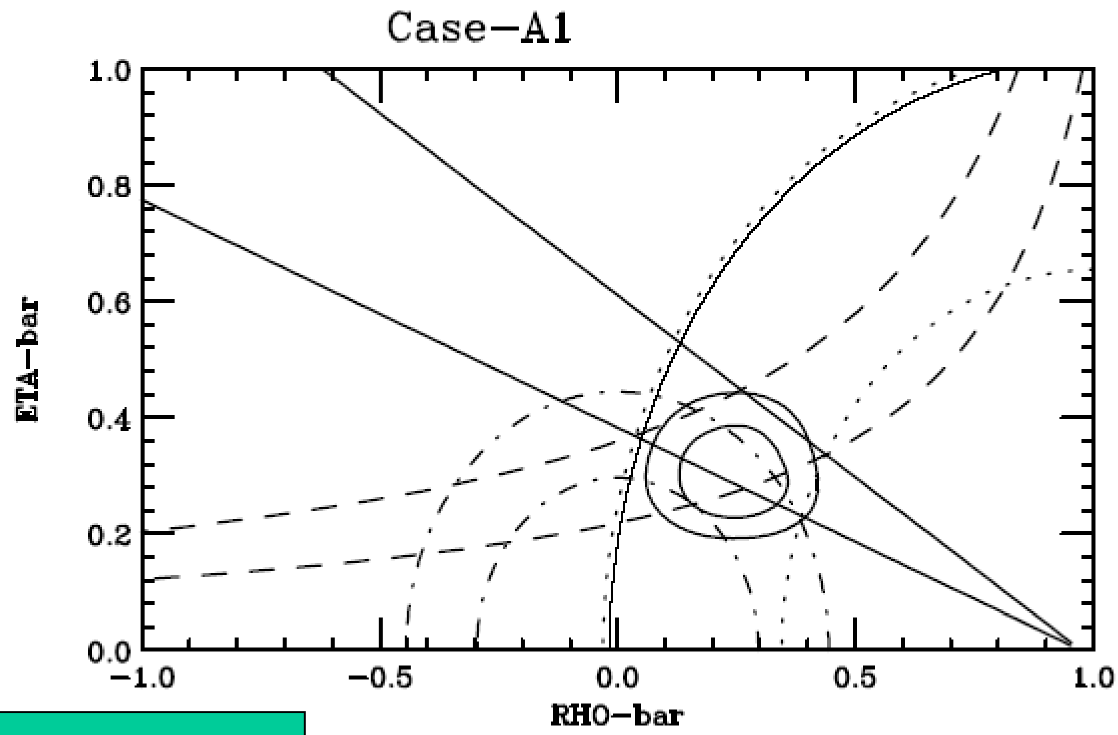


Figure 12.1: Graphical representation of the unitarity constraint $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ as a triangle in the complex plane.

The unitarity triangle

1st Hints of confirmation
Of CKM-CP violation

Atwood&A.S,
hep-ph/0103197



Most bands due
To theory errors

SM prediction using existing experiments + lattice input

Table 1: Comparison of some fits.

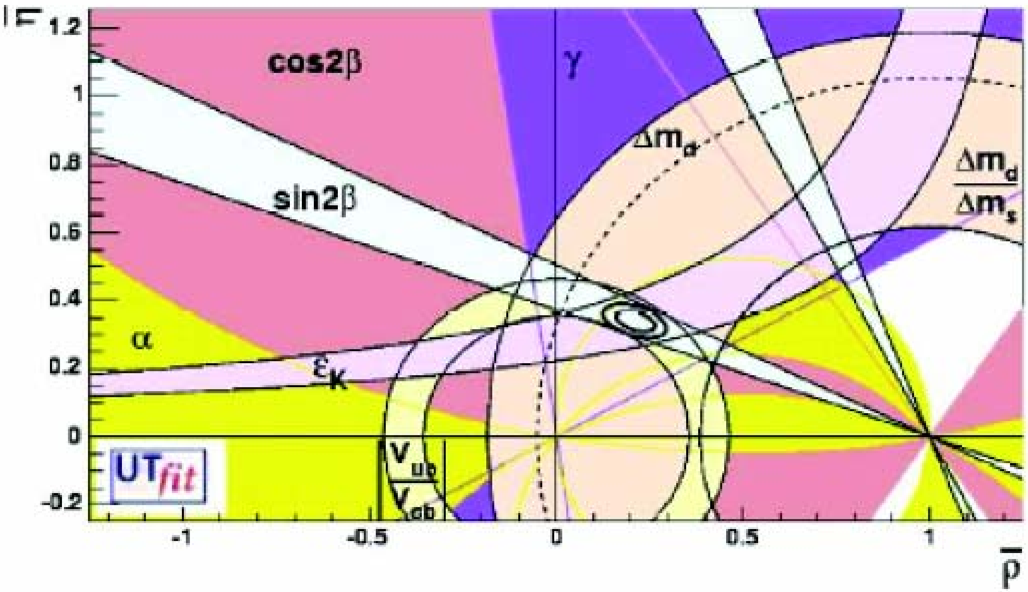
Input Quantity	Atwood & Soni[7]	Ciuchini *et al*[5]	Hocker *et al*[6]
$R_{uc} \equiv \lvert V_{ub}/V_{cb} \rvert$	$.085 \pm .017$	$.089 \pm .009$	$.087 \pm .006 \pm .014$
$F_{B_d}\sqrt{\hat{B}_{B_d}}$ MeV	230 ± 50	$230 \pm 25 \pm 20$	$230 \pm 28 \pm 28$
ξ	$1.16 \pm .08$	$1.14 \pm .04 \pm .05$	$1.16 \pm .03 \pm .05$
$\hat{B}_K$	$.86 \pm 0.15$	$.87 \pm 0.06 \pm 0.13$	$.87 \pm .06 \pm .13$
Output Quantity			
$\sin 2\beta$	$.70 \pm .10$	$.695 \pm .065$	$.68 \pm .18$
$\sin 2\alpha$	$-.50 \pm .32$	$-.425 \pm .220$	
γ	$46.2^\circ \pm 9.1^\circ$	54.85 ± 6.0	56 ± 19
$\bar{\eta}$	$.30 \pm .05$	$.316 \pm .040$	$.34 \pm .12$
$\bar{\rho}$	$.25 \pm .07$	$.22 \pm .038$	$.22 \pm .14$
$\lvert V_{td}/V_{ts} \rvert$	$.185 \pm .015$		$.19 \pm .04$
$\Delta m_{B_s} (ps^{-1})$	19.8 ± 3.5	$17.3^{+1.5}_{-0.7}$	24.6 ± 9.1
J_{CP}	$(2.55 \pm .35) \times 10^{-5}$		$(2.8 \pm .8) \times 10^{-5}$
$BR(K^+ \to \pi^+ \nu\bar{\nu})$	$(0.67 \pm 0.10) \times 10^{-10}$		$(.74 \pm .23) \times 10^{-10}$
$BR(K_L \to \pi^0 \nu\bar{\nu})$	$(0.225 \pm 0.065) \times 10^{-10}$		$(.27 \pm .14) \times 10^{-10}$

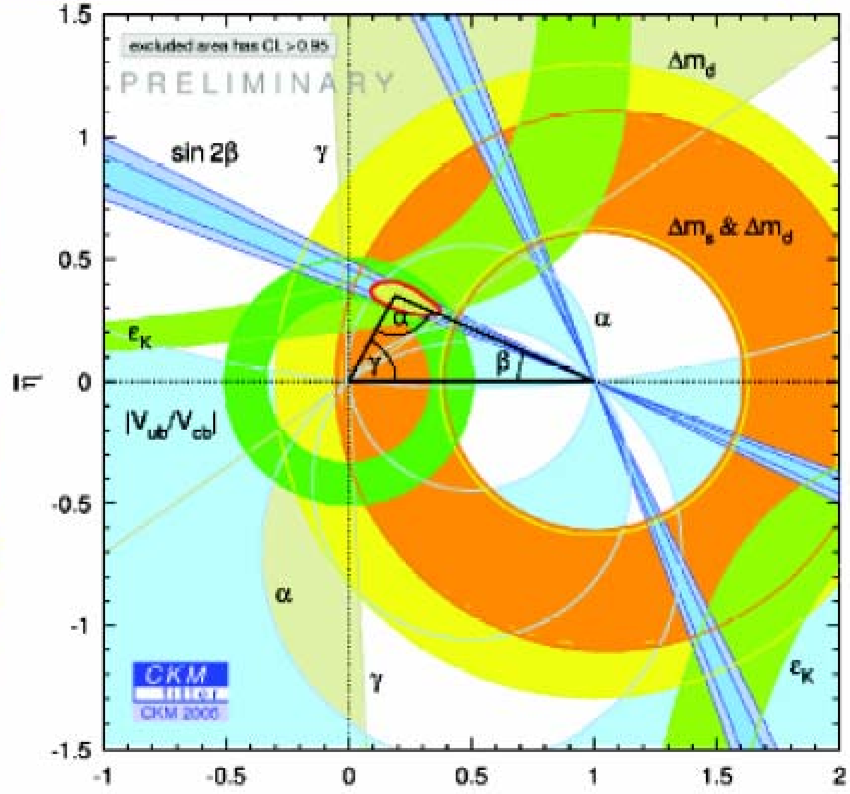
Table 31: $S_{b \to c\bar{c}s}$ and $C_{b \to c\bar{c}s}$.

Experiment		$-\eta S_{b \to c\bar{c}s}$
BABAR	[192]	$0.722 \pm 0.040 \pm 0.023$
Belle	[58]	$0.728 \pm 0.056 \pm 0.023$
B factory average		0.725 ± 0.037
Confidence level		0.91
ALEPH	[193]	$0.84^{+0.82}_{-1.04} \pm 0.16$
OPAL	[194]	$3.2^{+1.8}_{-2.0} \pm 0.5$
CDF	[195]	$0.79^{+0.41}_{-0.44}$
Average		0.726 ± 0.037

Heavy-flavor -averaging Group,hep-ex /0412073

Excellent agreement -> striking confirmation of the CKM-paradigm





$\bar{\rho} = 0.210 \pm 0.035$
[0.139, 0.276] @ 95% CL

$\bar{\eta} = 0.340 \pm 0.020$
[0.300, 0.380] @ 95% CL

$\bar{\rho} = 0.207^{+0.035}_{-0.045}$

$\bar{\eta} = 0.339^{+0.026}_{-0.021}$

Lattice helps attain an important milestone in Particle Physics

- **I. B-factory results + lattice (despite severe limitations)**

  -> CKM-paradigm of CP violation gives an excellent account simultaneouly of CP violation in K_L->ππ (ε_K~.001) as well as a_{CP} (B->ψK_S)~.73[SLAC/KEK] with

  η~.30+-.05!

- **II. Note w/o the lattice ~$1 billion spent for the experimental #s would have been seriously shortchanged.**
- **III. This is an outgrowth of the calculation of weak matrix elements initiated in collaboration with Claude Bernard ~'83.**

20 years of B_K

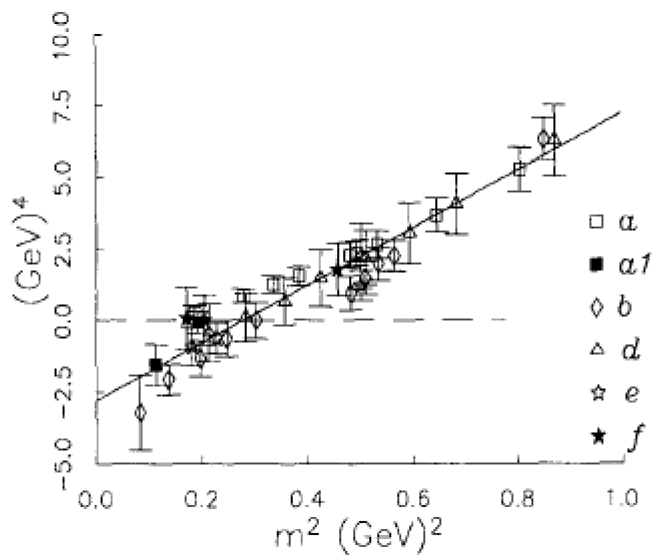


FIGURE 4

The amplitude $\langle \bar{K}^0|(\Delta s = 2)_{LL}|K^0\rangle \times 10^2$ vs. m^2. The solid line is a naive (uncorrelated) fit to the data.

$\langle \bar{K}^0|(\Delta s = 2)_{LL}|K^0\rangle$ with Wilson fermions has been proposed in Ref. 32. One starts by writing the CPTh form for the matrix elements of the continuum (physical) operator and for its Wilson lattice counterpart:

$$\begin{aligned} \langle \bar{K}^0|(\Delta s = 2)_{LL}|K^0\rangle^{cont} &= \gamma(p_K \cdot p_{\bar{K}}) + \cdots \\ \langle \bar{K}^0|(\Delta s = 2)_{LL}|K^0\rangle^{latt} &= \alpha + \beta m^2 + \gamma'(p_K \cdot p_{\bar{K}}) + \cdots, \end{aligned} \tag{8}$$

where the α and β terms in the lattice amplitude (and the change from γ to γ') are due to "bad" chirality operators such as $O'_\pm$ which have not been correctly removed by perturbation theory. Note that for K, $\bar{K}$ at rest, $p_K \cdot p_{\bar{K}} = m^2$; while for the crossed amplitude $\langle \bar{K}^0\bar{K}^0|(\Delta s = 2)_{LL}|0\rangle$, $p_K \cdot p_{\bar{K}} = -m^2$. Both the original $K^0 - \bar{K}^0$ amplitude and the crossed amplitude are then computed at rest on the lattice for various values of m, and the γ' term is extracted by a fit to the data. Finally, with the assumption $\gamma \simeq \gamma'$ (see below for a critique), the order m^2 term in the continuum ampli-

Bernard & A.S.
Lattice '88

C.Dawson

Operator Mixing and B_K ...

- If chiral symmetry is broken, four other operators can mix (the four other possible gamma matrix structures)

$$\langle \overline{K^0} | O_{VV+AA} | K^0 \rangle_{\text{latt}} \propto \langle \overline{K^0} | O_{VV+AA} | K^0 \rangle_{\text{ren}} + \sum_{i \geq 2} c_i \langle \overline{K^0} | O_{MIX,i} | K^0 \rangle_{\text{ren}}$$

These operators, of course, have a different chiral structure.

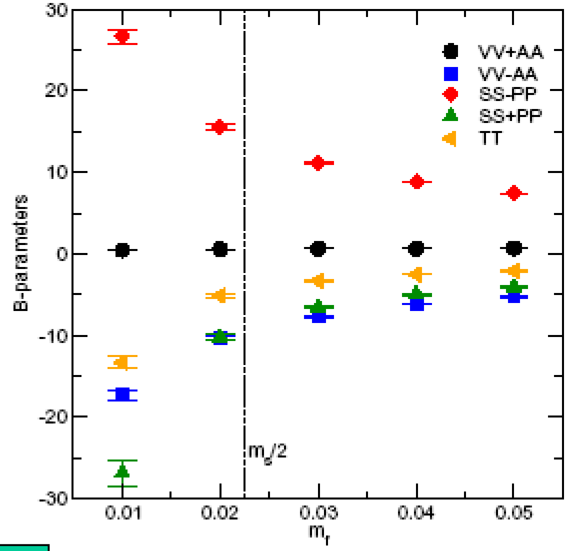
Mixing is hard to control using perturbation theory; First order chiral perturbation theory predicts that

$$\langle \overline{K^0} | O_{VV+AA} | K^0 \rangle \propto M_k^2$$

and,

$$\langle \overline{K^0} | O_{\text{THE REST}} | K^0 \rangle \propto \text{constant}$$

small enough mass, wrong chirality operators will dominate .

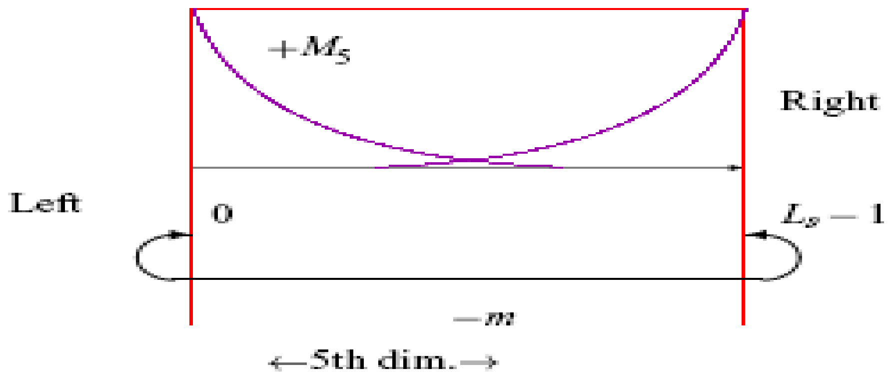


Lack of chiral symmetry becomes a fine-tuning problem!

EXACT CHIRAL SYMMETRY ON THE LATTICE

Conventional fermions do not preserve chiral-flavor symmetry on the lattice (Nielsen - Ninomiya Theorem) $\Rightarrow \Delta S = 1, \Delta I = 1/2$ case mixing with lower dim. (power-divergent) operators & or mixing of 4-quark operators with wrong chirality ones makes lattice study of $K - \pi$ physics virtually impossible.

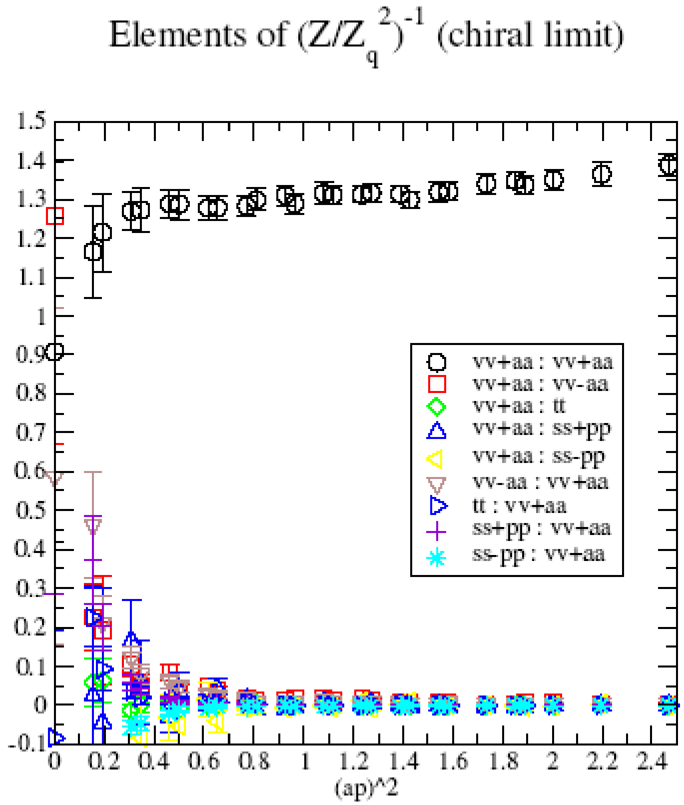
Domain Wall Fermions (Kaplan, Shamir, Narayanan and Neuberger)



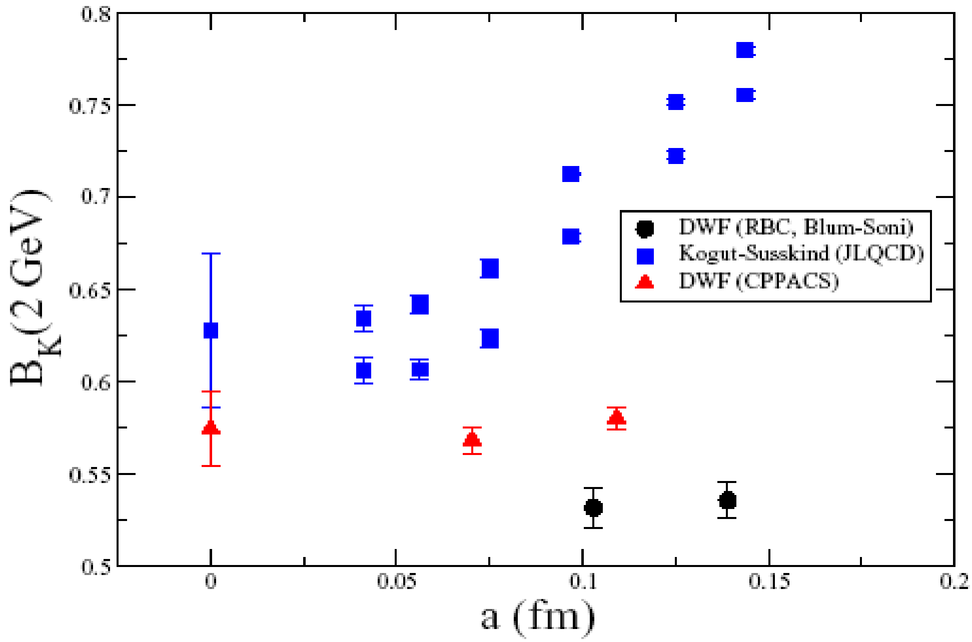
Practical viability of DWF for QCD demonstrated (96-97) Tom Blum & A. S.
Chiral symmetry on the lattice, $a \neq 0$! Huge improvement
$\Rightarrow$ Now widespread use at BNL and elsewhere

C Dawson@CKM'05

Z_{B_K} results



- Mixing very small
- Combining Diagonal Z with perturbative matching calculation give the Z-factor in $\overline{MS}$, as required.



B_K **with DWF's confronts staggered fermion results**

Indications are that DWQ answer is 10-15% below the old (staggered) result $\Rightarrow$ tends to correspondingly increase the CP violating phase $\bar{\eta}$ of the SM.

RBC, in prep.

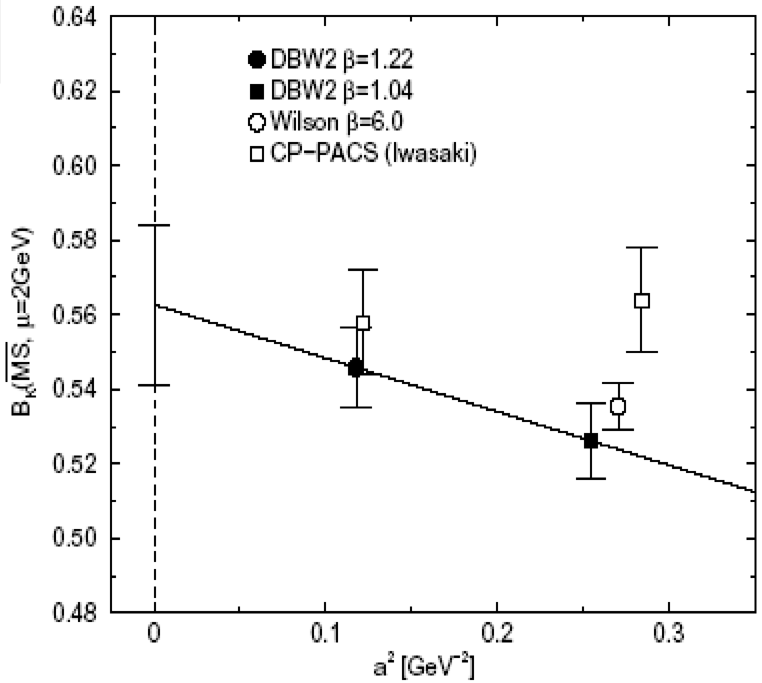


FIG. 29: Summary of our results of $B_K(\overline{\rm MS}\,{\rm NDR},\ \mu = 2\ {\rm GeV})$ renormalized with $N_f = 0$ as a function of the lattice scale squared. While filled circles are our results, open symbols are quoted from previous works [20, 21].

theory. Within the quenched approximation, we extrapolate to zero lattice spacing and obtain $B_K^{\overline{\rm MS}\ \rm NDR}(\mu = 2\,{\rm GeV}) = 0.563(21)(-25)$, where the first error represents the statistical error and second one is the systematic error within our calculation. We also discuss other

Dynamical Domain Wall Fermions

3/2 years running on a 400GF partition of the 1TF QCDSP (the cell-phone supercomputer)

- 3 different dynamical masses
  - $0.5m_s \rightarrow m_s$
- two degenerate dynamical flavours
- $16^3 \times 32$; ($(2\text{fm})^3 \times 4\text{fm}$)
- 96 configurations/mass

Made possible by a lot of work on improving fermion algorithms and learning how the Domain Wall Fermion mechanisms success depends on the Gauge Action used.

- Note: this is the "less quenched" approximation.
  - dynamical u and d; quenched s quark.
  - Stepping stone to 3 flavour dynamical DWF on QCDOC

C. Dawson

Results for B_K

RBC,hep-lat/0411006

Fitting for valence and dynamical masses such that

$$0.02 \leq am_{\text{sea}}, am_{\text{val}} \leq 0.04$$

as for low valence masses the plateau quality is bad, and we wish to stay in the (relatively) low mass region to fit to NLO chiral perturbation theory

Fit	Bare Number	$\overline{MS}$, 2GeV
Degenerate	0.547(15)	0.509(18)
Non-degenerate	0.533(14)	0.495(18)

The difference between the degenerate and non-degenerate fits is within the quoted statistical error, but due to these errors being correlated it is actually statistically well resolved as a $2.8 \pm 0.03\%$ effect.

- In the quenched approximation studies using staggered fermions give [JLQCD, 1997]:

$$B_K(\overline{MS}, 2\text{GeV}) = 0.63(4)$$

Our quenched result with domain wall quarks is somewhat smaller: 0.563(21)(25)…this tends to increase η

C.Dawson

Future

- This is a picture of the first QCDOC machine, taken a few days before it was shipped off to Edinburgh in November. The second machine (RBRC) is completely constructed and is currently being debugged. A third machine (shared by the US lattice community) will follow very soon. Each machine is capable of 10 TFlops.

RBC Menu'05

A sample of the physics we wish to study on these lattices:

- Hadronic spectrum
- Light quark masses
- Topological charge
- $K \to \pi\pi$ decay
- Nucleon matrix elements
- Exotic hadrons, pentaquarks
- Neutron EDM
- Electromagnetic structure of hadrons
- η' meson
- Structure functions
- Decay constants
- Static quark potential
- Kaon B-parameter
- $K \to \pi l \nu$
- Excited nuclear states
- Nucleon decay.
- $g - 2$
- $U(1)_A$ problem
- Charm and bottom physics

With a factor of 20 or more in computing power, clearly we would like to do lots of important physics.Unfortunately, HET has ZERO lattice post-doc (traditionally have had at least one)

B versus K Unitarity Triangle

Traditionally, experiment plus lattice matrix elements are used for ε_K, $B_d - \bar{B}_d$ mass difference (Δm_d) and semi-leptonic $b \longrightarrow ue\nu$ to constrain the unitarity triangle (UT)

$\Longrightarrow$ There ε_K provided crucial (and the only known) CP violation info. However, now that B-factories have seen large CP violation in $B \longrightarrow \psi K_s$ and it is very "clean", i.e. no hadronic uncertainties, one can replace input from ε_K in the above and construct UT purely from B-physics.

$\Longrightarrow$ In the future it would be important to construct another UT purely from K-physics using (greatly improved calculations) of hadronic matrix elements from the lattice, for ε_K, ε' along with improved experimental measurments of $K^+ \longrightarrow \pi^+ + \nu + \bar{\nu}$ and possibly also $K_L \longrightarrow \pi^0 + \nu + \bar{\nu}$.

$\Longrightarrow$ Comparison of the two UT's is likely to become a powerful new avenue to search for new physics.

Summary & Outlook

- **Lattice calculations of weak matrix elements along with B-factory results have led to a striking confirmation of the CKM-paradigm of CP violation.**
- **Since the KM-mechanism is dominant contributor to the observed CP violation in the K and B-systems, the effects of any new beyond the SM CP phase is likely to be small.**
- **This puts greater demands on precision from experiments as well as from theory for the discovery of new phenomena.**
- **For the lattice, the new hardware (QCDOC) would allow us to go beyond the quench approximation, a major source of error heretofore.**
- **To use the increased computing power effectively for physics applications of experimental interest, however, would require at least one possibly more lattice post-docs in HET; currently we have none.**